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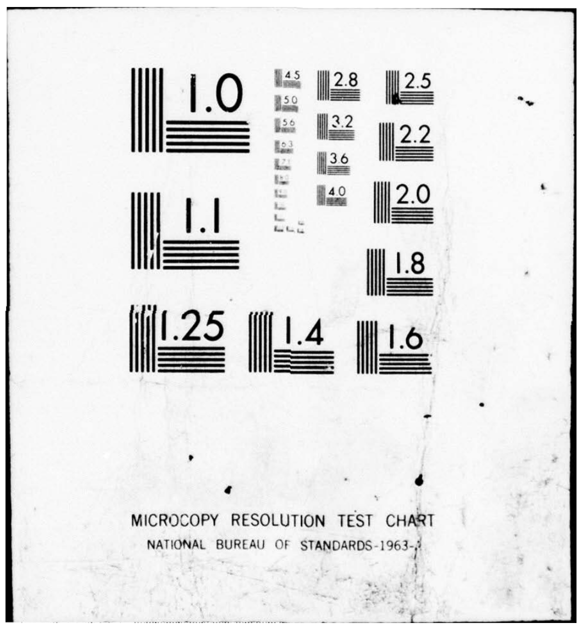
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Research and Development Technical Report
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FORTY KILOVOLT MEGAWATT AVERAGE POWER THYRATRON (MAPS 40)

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February 1979

Second Final Report for Period 15 September 1977 through 15 August 1978

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this 12 month program was to fabricate eight prototype MAPS-40 thyratrons to the design specifications derived during the original phase of this contract and thereby:

(1) Assess the reproducibility and operating consistency of the developed tube, and
(2) Provide ERADCOM with a number of sample tubes for experimental purposes.

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Results confirm the satisfactory performance obtained with the early developmental samples. Consistency in electrical performance, indicative of reproducibility was observed.

TABLE OF CONTENTS

1. INTRODUCTION

The purpose of this Final Report Addendum is to summarize the work performed for the U.S. Army Electronics R&D Command, Fort Monmouth, New Jersey, during the second phase of the MAPS-40 development program, under Contract No. DAAB07-76-C-1352, Modification No. P00001, between September 15, 1977, and August 15, 1978.

The main purpose of this work was to fabricate eight prototype samples built to the design developed during the R&D phase of the project. Two other objectives were to perform a titanium reservoir analysis and evaluation, and also a thermal analysis and evaluation of the MAPS-40 grid structures.

Aside from minor procurement problems, the fabrication, aging, and testing of the eight thyratron switches followed a smooth and consistent pattern, culminating in the timely and successful completion of the project. This portion of the work is outlined in the main body of the present addendum. The results of the grid and reservoir analysis and evaluations are presented in the attached Appendices.

2. PROTOTYPE TUBE MANUFACTURE

Fabrication of the eight MAPS-40 prototype tubes followed, with the exception of minor details, the procedure established for the last two development samples of the earlier phase of the program. The tubes were essentially "handmade" from machined parts fabricated and procured under strict quality control. Assembly was carried out under close engineering supervision. Slight variations in processing were introduced to observe corresponding changes in performance. No significant correlation was obtained from these exploratory attempts.

All eight tube assemblies were processed and delivered to ERADCOM. A few individual subassemblies, such as anodes, grids, etc. — about seven in all — were rejected during the course of manufacture but no completed tube assembly was lost. Subsequent aging and testing revealed these tubes to be consistent in their performance.

One tube, serial number 008, developed an open reservoir heater after some 30 hours of operation. The reservoir was replaced and the tube was reprocessed and delivered successfully before the end of the project.

A new, improved reservoir of enhanced reliability, described in Appendix A, was also fabricated during this period. The assembly procedure of the new MAPS-40 cathode was also refined during the program and one of these units was successfully constructed.

3. PROTOTYPE TUBE TESTING

Aging and testing of the eight prototype tubes at Fort Monmouth took place under the controlled conditions stated in the Final Report of October 1977. In all instances, the tubes were aged in progressive steps up to the megawatt average power level, but in the case of the last two samples, the original pattern of continuous operation at low repetition rates to the upper voltage limit, followed by burst mode aging at successively higher repetition rates, was not followed. Variations consisted of aging in the burst mode at the highest repetition rate required in ascending voltage steps, as well as starting with low repetition rates and jointly increasing voltage and pulse repetition rate.

All eight tubes constructed and delivered, serial numbers 7 through 14, met the full power specification at ERADCOM. Table 1 summarizes the performance of these tubes and compares them with the specification objectives. It should be noted that the majority of these prototypes were operated into a liquid copper sulfate load at di/dt levels in excess of 40 kA/μs.

Since all of the consecutively built tubes met the specified electrical performance, aging time may be substituted as a secondary criterion of design quality and fabrication consistency. Table 2 presents approximate aging times needed in each instance to reach full power. The observed variation is considered to be well within the bounds of normal thyratron aging experience at lower power levels. More remarkable is the speed with which some of these samples aged to the megawatt average power level.

Some additional information was obtained in the course of exploratory tests of the nominal design limits of the tube.

Table 1. Representative Performance of Developmental and Prototype MAPS-40 Thyratrons.

Parameter (units)	Specification Objectives: Rating	Specification Objectives: Operation (1)	Representative Performance: Full Power Test	Special Tests (1) Highest Peak Current	Special Tests (2) Continuous Operation	Special Tests (3) Highest Voltage
epy (kV)	40	44	44	40	36	50
ib (kA)	40	44	44	75	36	50
egy (kV)	1.5 to 4.0	—	2	—	—	—
tp (μs)	—	10	10	—	—	—
prr (Hz)	500	125	125	—	77	50
Ib (A dc)	50	50	50	—	20	24
Ip (kA ac)	1.48	1.48	1.48	—	0.85	1.1
Pb (10^9 va/s)	400	242	242	—	—	—
dik/dt (kA/μs)	20	20	20/40	75	36	50
td (μs)		0.2	<0.2	—	—	—
Δ tad (μs)		0.1	<0.1			
tj (μs)	0.02	—	<0.02			
Ef (Vac)	15±1.5	—	—			
Eres (Vac)	15±1.5	—	—			
If (A ac)	70	—	66			
Ires (A ac)	40	—	40			
tk (sec)	900	—	1200			
Life (pulses)		5×10^6	*			

*1×10^{-6} pulses have been achieved to date on two tubes. One (S/N 006) shows some degradation in high voltage reliability. One (S/N 014) still is operating without degradation, with about 1 kickout per 100,000 shots. Life data are being taken with 15-second runs at 40 kV and 50 Adc, with 3-1/2 minute off periods. Further details of these tests along with kickout history, are given in Appendix C.

Table 2. Aging Characteristics of Prototype MAPS-40 Thyratrons.

Prototype Tube Serial Number	Aging Time to 1 MW Average Power	Number of Kickouts
7	16	>10
8	8	<10
9	8	>10
10	24	>25
11	12	<10
12	20	>25
13	8	<10
14	16	<10

In a peak current test, the thyratron was operated into a 0.25-ohm load at 40 kV, switching a peak current of 75 kA. The 70 to 80 kA ultimate design limit due to quenching was confirmed.

In an average current test, the thyratron was subjected to continuous operation for 30 minutes at 40 kV and a pulse repetition rate of 50 Hz, giving an average current of 20 A. The thyratron operated well throughout this interval, but additional cooling was required.

In a high voltage test, one tube was run at 50 kV at the 0.5-megawatt power level without difficulty, showing that the single gradient grid will allow higher voltages to be reached at these power levels.

The results of these three special tests are summarized in the last three columns of Table 1.

4. PERFORMANCE APPRAISAL

Based on the test results obtained to date on four developmental and eight prototype MAPS-40 thyratrons, it can be stated that, to the extent that it has been possible to test and evaluate them, the inherent design of these tubes is capable of meeting the electrical requirements of the USAERADCOM specification.

The operational limits of the tube have been probed by means of the special tests listed in Table 1. While indicative of the tube's capabilities, these results should not be regarded as the last word, without further evaluation and/or confirmation in the near future.

Design feasibility has been established and, allowing for minor refinements, tooling, etc., the MAPS-40 seems ready to enter the preproduction stage, on the strength of its demonstrated performance characteristics.

5. PROGRAM STATUS SUMMARY

The results of the primary R&D and secondary prototype fabrication phases of the MAPS-40 program have convincingly demonstrated the ability of the MAPS-40 switch design to meet the electrical specification objectives set forth by USAERADCOM.

The weight of the tube exceeds the specified limit of 25 pounds but this is not considered a critical parameter for ground-based applications. Life and reliability objectives will be evaluated in the coming months. Limited results obtained to date extrapolate favorably toward the objectives and provide a high confidence level for their achievement. The reservoir performance and characteristics have been corrected and improved with a new design.

The prototype switches constructed to date are essentially "handmade," and a refinement phase, such as that provided by a Manufacturing Methods Program, is regarded necessary, prior to the start-up of any volume production activity.

The upper reaches of the MAPS-40 remain uncharted in some specific areas and it seems worthwhile to fill in existing performance gaps as conditions permit.

A-049-130

6. ACKNOWLEDGMENTS

The writers are again indebted to Messrs. J. Creedon and S. Schneider for support and encouragement throughout the project. We are also pleased to acknowledge the cooperative assistance of J. McGowan and H. Gauch in connection with various phases of aging and testing of the MAPS-40 thyratrons at Fort Monmouth.

N. Reinhardt carried out the analytical and experimental work on the titanium reservoir. T. Lynch contributed the thermal analysis of the grid structures of the tube.

G. Clark's assistance with respect to assembly and processing was highly effective. The assembly skills of W. Buttkus and H. Kruger were indispensable to the successful outcome of the program.

7. CONCLUSIONS AND RECOMMENDATIONS

While the design feasibility of the MAPS-40 thyratron has been firmly established by the outcome of this phase of the program, many possibilities exist for refinement and cost reduction. Weight, cost, complexity, and assembly time can all be reduced, but a concerted Manufacturing Methods Program is needed in advance of any volume production.

The full capability of the MAPS-40 has not been determined in all areas of performance. The ultimate performance of the tube should be assessed in terms of pulsed, burst mode, and continuous operation, as circumstances permit, in the near future.

APPENDIX A
TITANIUM RESERVOIR ANALYSIS, DESIGN, AND EVALUATION

The Old Reservoir

The original reservoir developed specifically for the MAPS-40 thyratron was intended to have fast response and a large hydrogen storage capacity. It took the form of two 100-gram rings of edge-wound titanium strips with a flat-sheet heater sandwiched between them, arranged to fit the annular space between the central group of MAPS-40 feed-through conductors and the outer wall of the envelope. Tests of the principle of applying heat to one face of the edge-wound ring and radiating it away from the opposite face (with metallic conduction taking place across the width of the strips forming the ring) showed that this was indeed the way to obtain prompt and uniform warmup of a fairly thick laminated slab of titanium having a large surface area. The reservoirs made according to this principle showed much more rapid response to power changes than we were accustomed to seeing in reservoirs made of powder or stacked flat plates.

In the course of developing the MAPS-40, however, the concept of a reservoir in the shape of a simple ring to fit the annular space described became badly compromised when it turned out to be advisable to solidly and permanently braze the heat isolating septum (the "sole plate") to heavy copper bus-bar conductors similarly brazed to the base of the tube. Topologically, there was no way of sliding a closed ring into the resulting toroidal space.

An arbitrary, brute-force expedient was adopted. The ring reservoir was divided into quadrants, which could be individually snaked into place and connected independently to the reservoir feed-through, a process similar to building a boat in a bottle. The resulting complications of support and current-feed combined to eventually defeat the use of a segmented ring in this

manner; from the outset, chronic trouble with heater shorts was encountered, due to (1) asymmetrical disposition of the heater within its heater space, with resulting pinching and crowding under the influence of thermal expansion differentials, (2) an off-center mounting arrangement which did not support the reservoir symmetrically with respect to its center of gravity, giving rise to couples in shock and vibration, and (3) forces on the heater connections transmitted from the long, heavy, and vibration-prone heater connection harness. Various strain-relief features added later as palliatives proved to be of only uncertain effectiveness, particularly after the reservoir materials of construction relaxed their tension and became weaker during prolonged exposure to heat.

At the same time, a curious kink was noted in the pressure response behavior of these reservoirs. This was at first ascribed to temperature or warm-up rate differences between different parts of the structure, for indeed, the cut-up segments were observed to be running significantly colder at their extremities. Since the heater, a boustrophedon design with short bars, was known to heat nonuniformly, a first attack was made by substituting a heater with a fully compensated circular mesh design, in which the resistance of each circular arc element was made inversely proportional to the radius, and all interstices or hairpin turns were compensated similarly. This rather elegant heater (Figure A-1) did indeed heat uniformly and well, but it did not solve the problem of the "kink," which manifested itself as inability to change hydrogen pressure over a wide range of reservoir settings, or in extreme cases, the obtaining of the same hydrogen pressure at three different reservoir voltages, with inflective excursions of pressure between them.

Accordingly, controlled loading versus pressure and temperature curves were run to establish what was indeed happening. Accurate measurements showed that in trying for rapid response, we had inadvertently entered a region of pressure vs. temperature ambiguity implied in McQuillan's original data on the hydrogen-titanium system, but heretofore not directly encountered in our work on these reservoirs. Therefore, in addition to the mechanical problems described above, we had arrived at a fundamentally wrong operating point.

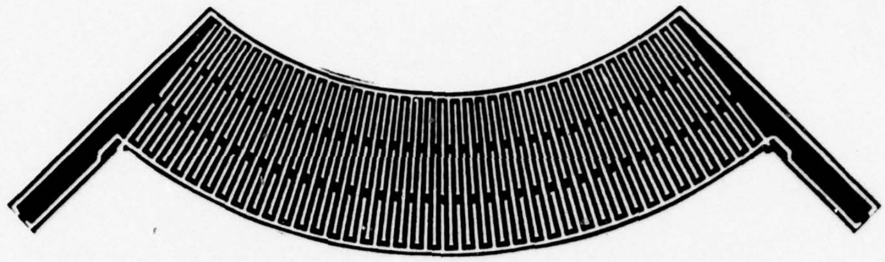

Figure A-1. New Heater for Circular Sector, Old Reservoir.

With a patched but still only marginally reliable reservoir and heater structure, now very difficult to build, and an actual operating point in a region of pressure instability, a redesign was inevitable.

<u>The New Reservoir</u>

An improved MAPS-40 reservoir, shown in Figure A-2, has been designed, built, and tested, in which the objects of simplified assembly, freedom from heater shorts, and improved pressure stability have apparently been achieved.

This reservoir, like earlier ones, consisted of two sets of edge-on titanium strips, with a flat heater sandwiched between them. In this reservoir, however, the complications of the earlier quadrant-sector shape have been eliminated by making the enclosure rectangular, and mounting the resulting box on sturdy, well-braced legs. The resulting loss in area, due to the less-form-fitting shape, has been made up by increasing strap width from 0.1 to 0.2 inch, the extra width having no evident effect on overall warm-up or response to voltage adjustments. The long, relatively weak, and heavy connection harness has been replaced by a light, stiff harness firmly tied to the reservoir enclosures by ceramic bushings. It should be immune to handling shock and vibration. The heater is isolated within a separate heater enclosure, where it remains undisturbed by motion or strains transmitted from outside.

In the redesign, the opportunity was taken to lower the operating temperature and increase the gas loading. The loading of the new reservoir was checked and found to be approximately 130 liter-torr per reservoir section, or about 1.2 liter-torr per gram of active material, at the nominal fill pressure of 0.3 torr, or a total of 520 liter-torr for a 4-section reservoir, at a nominal heater power of 550 watts. When filled to 0.3 torr and ranged, pressure behavior is stable up to 0.7 torr, the pressure varying monotonically with watts raised to the 2.2 power (in common with most titanium-hydrogen reservoirs). Figure A-3 shows the comparative behavior of the old reservoir, with original and new heaters, and of the new rectangular reservoir.

If rapid response time is not badly needed, it may be useful to back up to about 70% of the nominal heater power to a more conservative operating point, where the reservoir will hold perhaps four times as much gas, and the 2.2-power relation will hold up to much higher hydrogen pressures (initially well over 1 torr), and remain stable throughout tube life.

Tubes utilizing the redesigned reservoir are now under construction, and will be undergoing further test and evaluation in the coming weeks.

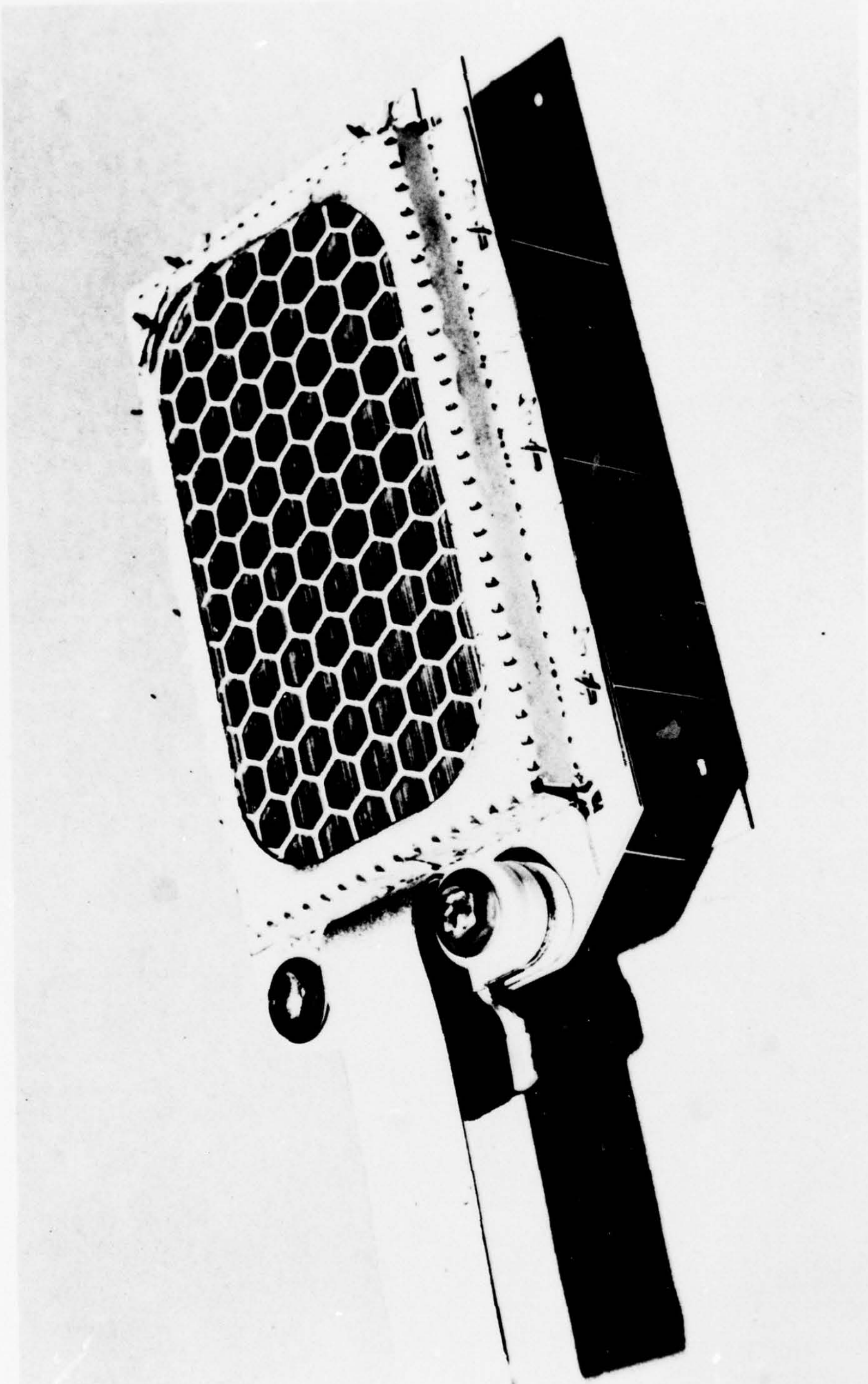

Figure A-2. New, Completely Redesigned Rectangular Reservoir.

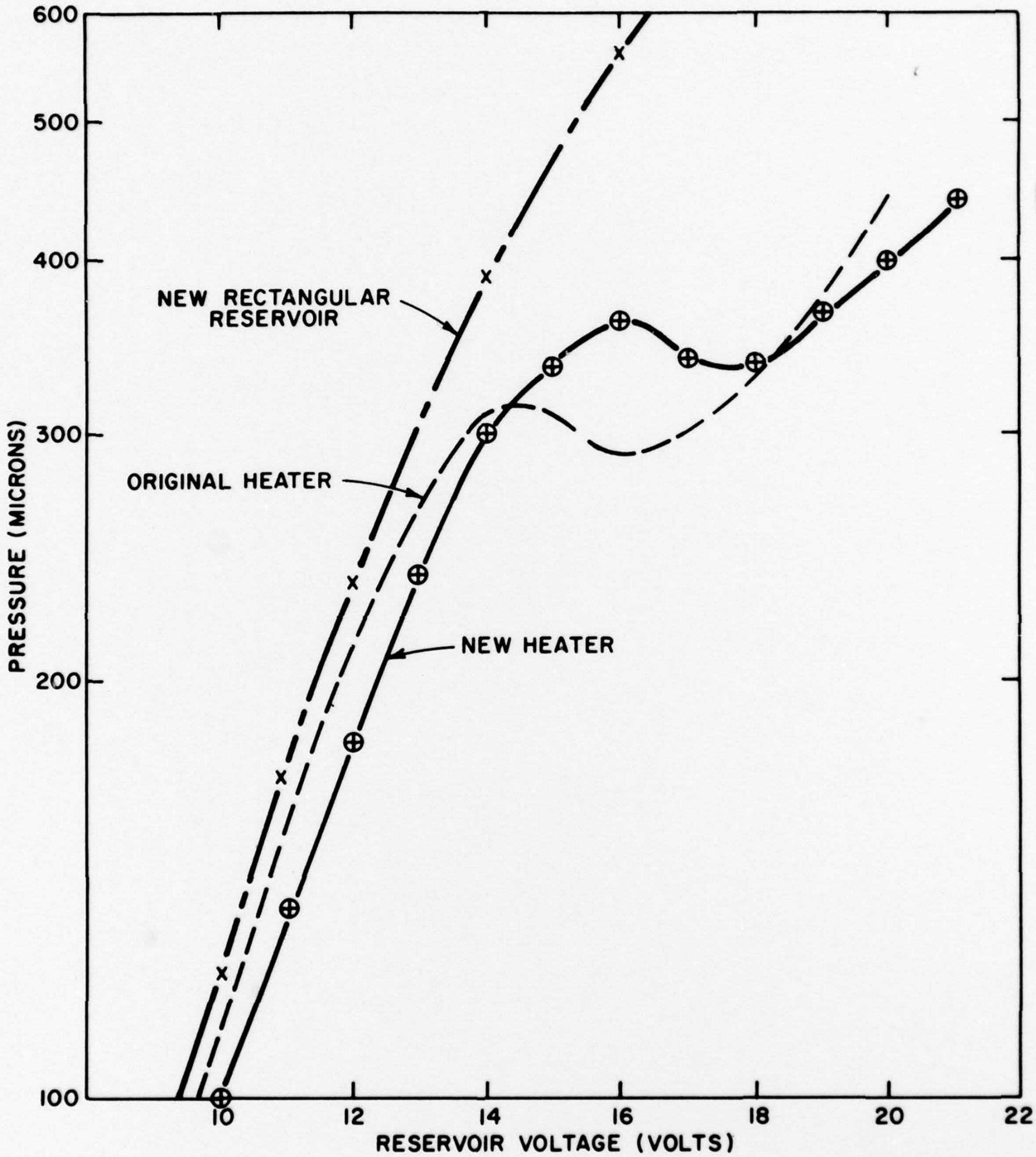

Figure A-3. Pressure-Voltage Characteristic of New Rectangular Reservoir.

If rapid response time is not badly needed, it may be useful to back up to about 70% of the nominal heater power to a more conservative operating point, where the reservoir will hold perhaps four times as much gas, and the 2.2-power relation will hold up to much higher hydrogen pressures (initially well over 1 torr), and remain stable throughout tube life.

Tubes utilizing the redesigned reservoir are now under construction, and will be undergoing further test and evaluation in the coming weeks.

APPENDIX B

THERMAL ANALYSIS AND EVALUATION OF MAPS-40 GRID STRUCTURES

Introduction

A thermal analysis of the Control Grid and the Gradient Grid structures was performed to determine the temperature difference across the various elements as a function of heat load. Steady state conduction was considered, with the heat load uniformly applied on the appropriate grid over an annulus of 0.6-inch inside radius and 3.1-inch outside radius and conducted to the cooling ring, which is considered mounted to a heat sink. All brazed joints were assumed 100% effective.

The heat capacities of the structures were also calculated.

Control Grid

Results

The calculated values of temperature difference across the various elements of the Control Grid structure for 1-kilowatt heat load are given in Table B-1. The values may be taken as constant thermal resistance (°C per kilowatt) except for the slight decrease in thermal conductivity at higher temperatures.

Table B-1. Calculated Temperature Differences Across Elements of Control Grid Structure.

Control Grid	Temperature Difference at 1 kW (°C)
Cooling Ring	78
Skirt	79
Radial Bars	105
Strip	7
TOTAL	269

Cooling Ring

Although the cooling ring/mounting flange is copper, it still accounts for a significant temperature difference since it carries the full heat load and is only 1/16 inch thick. (The contact resistance between the ring and the heat sink is not included.)

Skirt

The 1/8-inch thick copper conical skirt represents about the same temperature rise as the cooling ring. The model for the skirt considered that the heat input to the top is localized where the ten copper cooling bars attach. This results in about a 20% higher temperature difference than taking the heat as uniformly applied along the top surface of the cone.

Radial Bars

The "radial bars" are a composite of the copper cooling bars, the moly support bars, and the uncut radial portions of the grid and the baffle. The constriction due to the slots in the copper cooling bars was estimated to increase the temperature difference by 47% over an unslotted bar. The slotted copper bars represent 64% of the conductance of the composite. Each of the composite bars was considered to carry 1/10 of the total heat load, applied uniformly over the sector of an annulus of 0.6-inch inner radius, 3.1-inch outer radius, and an included angle of $\pi/5$ radians.

The bars represent the largest temperature difference, with the highest temperature gradients occurring near the outer edge where the heat flux in the bars is the greatest. This suggests tapered bars, with increasing width and/or depth. It may also be possible to decrease the width and depth of the slots in the copper bars to reduce the constriction.

Strip

This considers the circumferential strips of the grid between the cooling bars. With the uniform heat load on one surface of the strip, a length of 1 inch between bars, and moly thickness of 3/16 inch, the steady state temperature difference along the strip is very low compared to the other elements.

Heat Capacity

The heat capacity of the Control Grid structure consisting of the cooling ring, skirt, radial bars, grid, electrode skirt, and grid baffle was calculated to be 0.41 Btu/°F or 780 joules/°C. Therefore, the rate of temperature increase per kW of absorbed power, for all metal parts at the same temperature, would be 77°C/minute.

The grid alone has a thermal capacity of 0.12 Btu/°F, which is 29% of the total for the metal structure. Hence, if a heat pulse is absorbed only by the grid, causing its temperature to rise by Tg, and then the metal structure equilibrates adiabatically until a uniform temperature rise To exists, then

$$T_g/T_o = 1/0.29 = 3.5$$

Gradient Grid

Results

The calculated values of temperature difference across the various elements of the Gradient Grid structure for 1 kilowatt heat load are given in Table B-2.

Table B-2. Calculated Temperature Differences Across Elements of Control Grid Structure.

Gradient Grid	Temperature Difference at 1 kW (°C)
Cooling Ring	316
Radial Bars	307
Strip	14
TOTAL	637

Cooling Ring

The heat input to the 1/16-inch thick copper cooling ring is localized where the ten spacer bars are attached, since there is a gap of a nominal 0.019 inch between the grid and the cooling ring, preventing direct conduction. The flow of heat to the sink (taken at the mounting bolt circle) is constricted by the 3/4-inch long strain relief slots. (The contact resistance between the cooling ring and the heat sink is not included.)

The potential benefit of decreasing the length of the strain relief slot was calculated. The following are the temperature differences for the cooling ring at 1 kW:

Slot Length (inches)	Temperature Rise (°C)
3/4 (original)	316
1/2	255
No Slots	122

Radial Bars

The "radial bars" consist of the spacer bars and the uncut radial portions of the grids, for an overall size of 0.250-inch wide x 0.350-inch thick moly. Each of the bars was considered to carry 1/10 of the total heat load, applied uniformly over the sector of an annulus of 0.6-inch inner radius, 3.1-inch outer radius, and an included angle of $\pi/5$ radians.

Strip

This considers the circumferential strips of the grid between the radial bars. With the uniform heat load on one surface of the strip, a length of 1.2 inches between bars, and moly thickness of 1/8 inch, the steady state temperature rise along the strip is very low compared to the other elements.

Heat Capacity

The heat capacity of the Gradient Grid structure consisting of the cooling ring, spacer bars, gradient grids, and electrode shields was calculated to be 0.33 Btu/°F or 630 joules/°C. Therefore, the rate of temperature increase per kW of absorbed power, for all metal parts at the same temperature, would be 95°C/minute.

One grid alone has a thermal capacity of 0.091 Btu/°F, which is 27% of the total for the metal structure. Hence, if a heat pulse is absorbed only by the grid, causing its temperature to rise by Tg, and then the metal structure equilibrates adiabatically until a uniform temperature rise To exists, then

$$Tg/To = 1/0.27 = 3.7$$

APPENDIX C

LIFE TESTS OF TWO MAPS-40 THYRATRONS

Life tests were made on SN 014 and SN 006 using the ERADCOM MAPS-40 aging rack at 40 kA, 40 kV, 125 Hz, and 50 amperes average. The load was a 0.5 ± 0.1 ohm copper sulfate liquid resistor. The pulse width was a nominal 9 microseconds and the rise time between 10 - 90% points was 1 microsecond. A matched end of line clipper was used in all tests.

Tubes No. 014 and No. 006 were life tested for 500,000 pulses, wherein the duty was 15 seconds on and 3.5 minutes off. All kickouts were recorded. Time during the run at which the kickout occurred was also observed.

The starting sequence for each burst was to charge the PFN to an unloaded dc voltage at which 40 kV was obtained on the network at one megawatt average power loading. The grid was then snapped on for 15 seconds and then snapped off. As a result of this starting sequence, the network voltage was typically 26.4 kV for the first pulse, 44 kV for the second pulse, and 40 kV for all other pulses in the burst thereafter. The 10% overshoot on the second pulse was responsible for a large percentage of the total observed kickouts.

At the end of the 500,000 pulse life test, SN 014 was tested for an additional 500,000 pulses, where the on time was reduced from 15 to 10 seconds during the burst. All other conditions were left the same.

Total kickouts versus life are shown in Figure C-1. Figure C-2 shows the significance of the second pulse kickout. The lower two curves are for the 15-second tests performed first; the inability to hold off the 10% overshoot on the second pulse appears to onset after about 300,000 pulses. The cause of the degradation is not fully understood. Changes in the reservoir setting were made but there did not appear to be a correlation in the kickout rate with reservoir voltage.

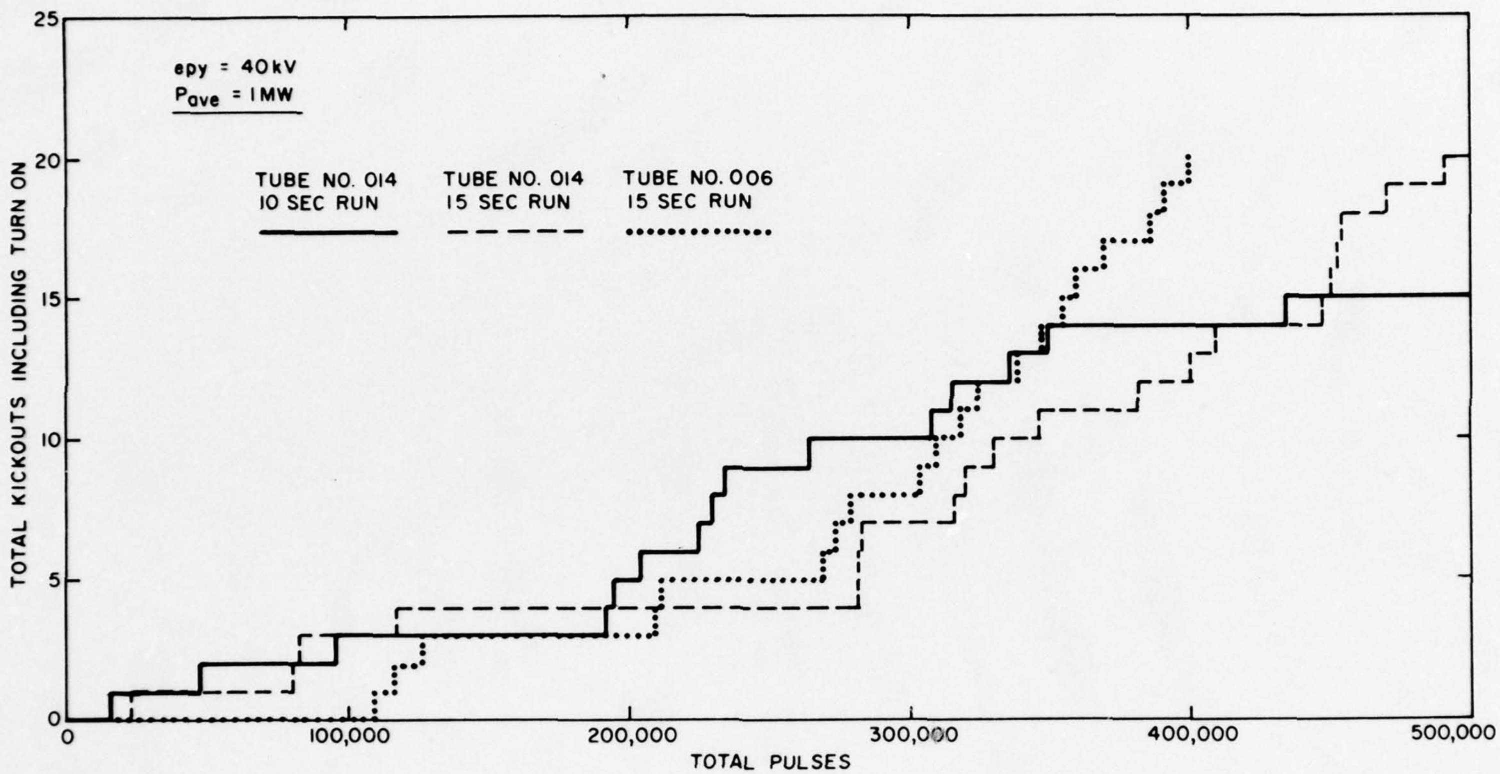

Figure C-1. Total Kickouts versus Life for Two MAPS-40 Thyratrons.

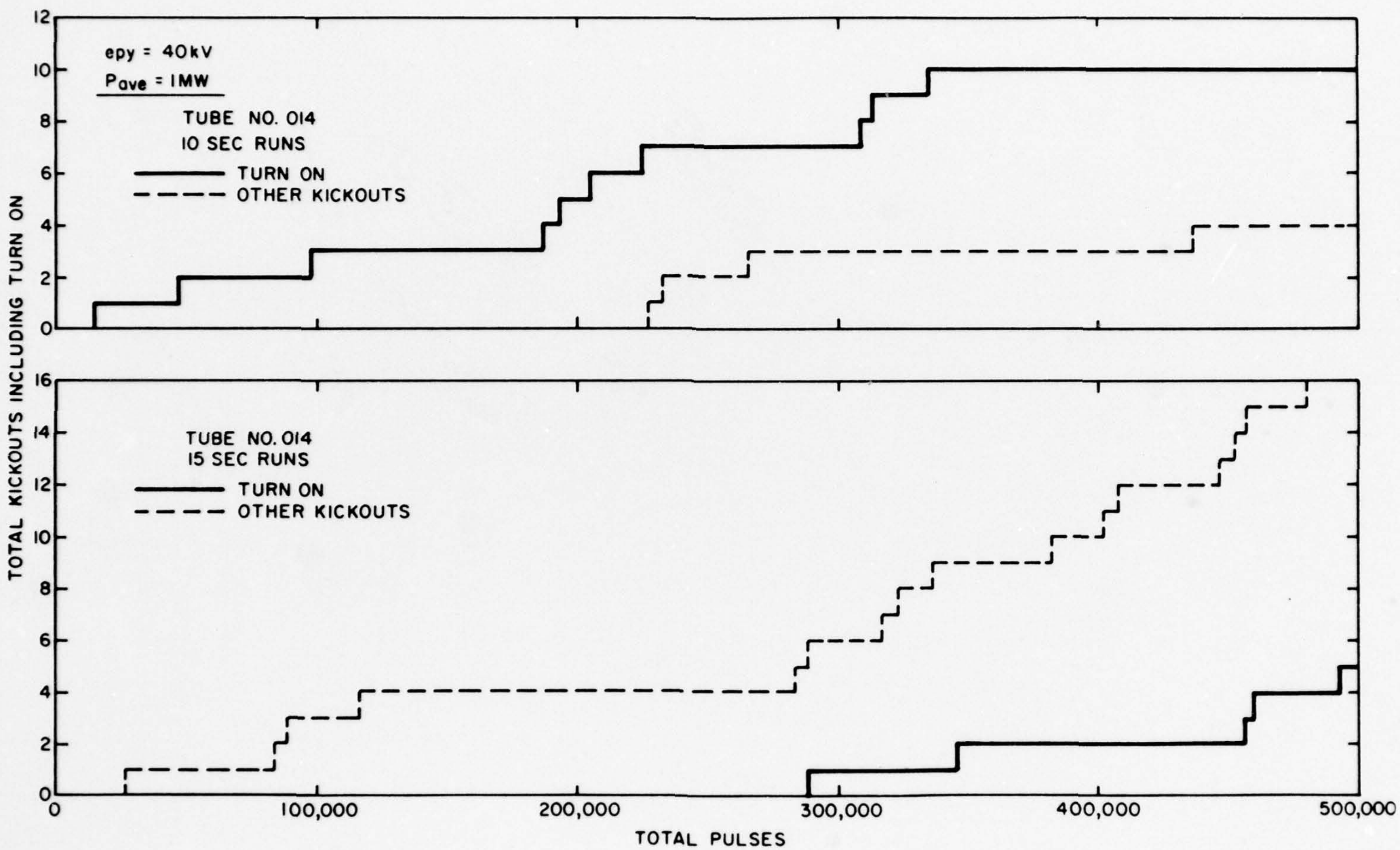

Figure C-2. Significance of Second Pulse Kickout.

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